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TWO-DIMENSIONAL ACOUSTO-OPTICAL INTERACTION THEORY AND EXPERIMENTAL ANALYSIS

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Abstract: In the paper, the universal coupling wave equation of two-dimensional acousto-optical interaction is theoretically derived. The solution of Raman-Nath diffraction under normal acousto-optical (A-O) interaction is derived from it. The theoretical results are compared with the experimental results of a two-dimensional A-O device consisting of two one-dimensional Raman-Nath type A-O modulators. These two results are in agreement with each other.

Key Words: coupling wave equation, Raman-Nath Acousto-optical (A-O) interaction, two-dimensional A-O interaction

I. Introduction

In 1976, by using the theory of parameter interaction in nonlinear optics, Chang et al. [1] established a unified theory of A-O interaction. The theory correctly interprets a series of phenomena and applications in the fields of Raman-Nath and Bragg

types as well as normal and abnormal A-O functions. However, the previous research was done in the one-dimensional situation. Since the A-O function can be realized in multiple dimensions (in other words, the same light beam can simultaneously interact with ultrasonic waves from several directions in the same A-O medium), thus the A-O diffraction effect can appear in multiple directions. The two-dimensional A-O diffraction effect is a typical example. As revealed in recent studies [2,3], this two-dimensional A-O function can be used to make multiposition switches, space-division repetitive-use device, and spatial light modulator, among other applications. So, the two-dimensional A-O function has extensive application prospects in optical computation, optical communication, optical information processing and optical exchange, among other areas.

Researched and developed by the authors, the two-dimensional Raman-Nath type A-O diffraction device is a key bistable apparatus for optical space coherence. However, the bistable optical spatial coherence will have important applications in coherence metrification, graphic encoding and optical computation.

II. Coupling Wave Equation of Two-dimensional Acousto-optical Interaction

Assume that the incident light is a monochromatic plane wave; its propagation direction and the x-z plane (and x-axis) form an included angle θ_0 (and θ_1). The circular frequency is W_0; the wave vector is k_0. The mode of wave vector k_0 is

$$k_0=\frac{2\pi n_0}{\lambda_0}, \qquad (1)$$

In the equation, λ_0 is the wavelength of light wave in vacuum; n_0 is the refractivity of incident light in medium (generally speaking, the polarization state of n_0 and incident light is related to the propagation direction). Assume that the circular frequency and wave vector of two beams of ultrasonic waves are

(ω_{1s}, K_{1s}) and $(\omega_2 s, K_{2s})$, respectively. The modes of wave vectors K_{1s} and K_{2s} are, respectively,

$$K_{1s}=\frac{2\pi}{\lambda_1}=\frac{2\pi}{v_1}f_1, \quad K_{2s}=\frac{2\pi}{\lambda_2}=\frac{2\pi}{v_2}f_2, \tag{2}$$

In the equation, λ_1 and λ_2 are wavelength of ultrasonic waves; f_1 and f_2 are the frequencies of ultrasonic waves; and v_1 and v_2 are the speed of sound. For sake of generality, assume K_{1s} is within the x-y plane; the included angle between K_{1s} and the x-axis is θ_a. K_{2s} lies within the x-z plane; the included angle between K_{2s} and x-axis is θ_β, as shown in Fig. 1.

Based on the principle of parametric interaction, the coupling of the incident light wave and the ultrasonic wave in the medium generates a series of polarized waves of composite frequency. The circular frequency $\omega_{p,q}$ and the wave vector $k_{p,q}$ are, respectively,

$$\left.\begin{aligned}\omega_{p,q}&=\omega_0+p\omega_{1s}+q\omega_{2s},\\ k_{p,q}&=k_0+pK_{1s}+qK_{2s},\end{aligned}\right\} \tag{3}$$

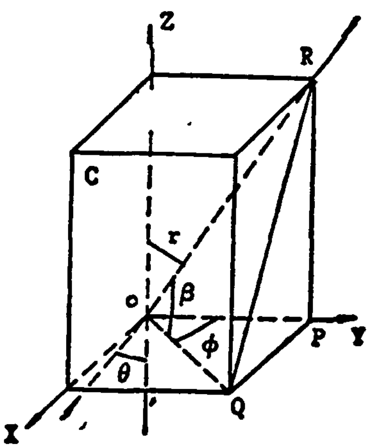

Fig. 1. Schematic diagram of acousto-optic interaction

In the equation, p, q = 0, ±1, ±2, ... These polarized waves stimulate light irradiation at the same frequency; that is, the various levels of diffracted light. Their total electric field is E(r,t), which can be expressed by the following expanded equation:

$$E(r,t)=\sum_{p,q=-\infty}^{\infty} e_{p,q}E_{p,q}(x)\exp[i(\omega_{p,q}t-k_{p,q}\cdot r)], \qquad (4)$$

In the equation, $e_{p,q}$ is the unit electric vector of the (p,q) diffraction level. It is assumed that the ultrasonic wave is a plane wave of a single-frequency; then, we can write out the corresponding acousto-optical function strain-tensor S(r,t) and nonlinear polarized vector P^{NL}. Vector $k_{p,q}$ of the free optical wave for the (p,q) level of diffracted light is stimulated by the polarized wave; when the incident light direction k_0 is random, generally $k'_{p,q}$ is not equal to $k_{p,q}$. Thus, as shown in Fig. 2, the momentum mismatch $\Delta K_{p,q}=k'_{p,q}-k_{p,q}$ is introduced. In the equation, $\Delta K_{p,q}$ is limited to the direction along the x-axis. Therefore, the mode of $k_{p,q}$ is $(n_{p,q}\omega_{p,q}/c)$; however, its direction makes $\Delta K_{p,q}$ along the x-axis. Thus, $\Delta K_{p,q}\doteq[(k'^2_{p,q}-k^2_{p,q})/2k'_{q,q}]$; let

$$\left.\begin{aligned} x_{1p,q}&=-n^2_{p,q}n^2_{p-1,q}P_1,\\ x_{2p,q}&=-n^2_{p,q}n^2_{p,q}P_2,\end{aligned}\right\} \qquad (5)$$

In the equation, P_1 and P_2 are the effective acousto-optical coefficients along the corresponding directions. Since $[dE_{p,q}(x)/dx]\ll k'_{p,qo}$, in the parametric interaction equation [5], the term $[d^2E_{p,q}(x)/dx^2]$ is neglected. In addition, considering the above-mentioned conditions, we derive

$$\frac{dE_{p,q}(x)}{dx}-i\Delta K_{p,q}E_{p,q}(x)=\frac{k^2_{p,q}}{4k'_{p,qo}}[n^2_{p+1,q}P_1S_1E_{p+1,q}(x)-n^2_{p-1,q}P_1S_1E_{p-1,q}(x)$$
$$+n^2_{p,q+1}P_2S_2E_{p,q+1}(x)-n^2_{p,q-1}P_2S_2E_{p,q-1}(x)], \qquad (6)$$

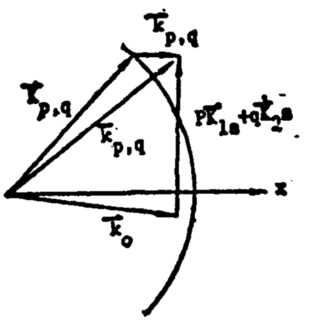

Fig. 2. Illustration of momentum mismatch

This equation is the cou ling wave equation of two-dimensional acousto-optical interaction. Thus, we can draw the following conclusions.

(1) When the length L of acousto-optical interaction is very small, due to momentum mismatch, the decrease in light intensity (induced by various levels of diffracted light) is not obvious; therefore, multilevel diffracted light can be generated. This is the Raman-Nath diffraction.

(2) When the length L of acousto-optical interaction is very large, all diffracted light of $\Delta K_{p,q} \neq 0$ is very faint. Formed by the incident light, the zero-level light is unable to couple with light other than the nearest four levels. Therefore, only by adjusting the direction of incident light so that any one of the four levels ($\Delta K(\pm 1,0)$ and $\Delta K(0,\pm 1)$) is equal to zero, then very strong diffracted light at this level can be obtained. This is the Bragg diffraction. We can see that the results of the two-dimensional Bragg diffraction and one-dimensional Bragg diffraction are the same. In other words, only two particular levels of diffracted light can be generated, including the level of (0,0).

III. Solution of Coupling Wave of Raman-Nath Equation

In the case of normal acousto-optical function, $\Delta n = -n^3PS/2$, all $e_{p,q}$ lie in the same direction, $n_{p,q} = n_0$. Generally, $\theta_s = \theta_s = (\pi/2)$. Define

$$\xi_1 = -\frac{2\pi \Delta n_1 L}{\lambda_0 \cos\theta_1}, \quad \xi_2 = -\frac{2\pi \Delta n_0 L}{\lambda_0 \cos\theta_1}, \qquad (7)$$

ξ_1 and ξ_2 represent, respectively, the phase shift of K_{1s} and K_{2s} induced by acousto-optical interaction. Thus, considering the randomness and independence of values for p and q, and by using the recurrence relationship of the Bessel functions, we can solve Eq. (6) and show that the efficiency of diffracted light at

various levels for Raman-Nath at vertical incidence is

$$\eta_{p,q}=J_p^2(\xi_1)J_q^2(\xi_2)。 \tag{8}$$

From the ultrasonic power $P_s=\frac{1}{2}\rho v^3|S|^2HL$, ρ is the density of the medium, V is the speed of sound, S is the strain, and H is the width of the transducer. Taking one step further, we obtain the relationship between the diffraction efficiency and the ultrasonic power, which is given by the following equation:

$$\eta_{p,q}=J_p^2(M_1\sqrt{P_{s1}})J_q^2(M_2\sqrt{P_{s2}}), \tag{9}$$

In the equation, M_1 and M_2 are parameters related to the acousto-optical modulator.

IV. Experimental Procedures and Results

The apparatuses used in the experiment include two-dimensional Raman-Nath acousto-optical modulators, made by the authors. These moduÜlators were made by adhering two one-dimensional Raman-Nath acousto-optical modulators of two acoustic fields that are orthogonal to each other. The crystal material was $PbMoO_4$; the acoustic field frequencies were f_{1s}=26MHz and f_{2s}=28MHz; the incident light wave $\lambda_0=6328\,\text{Å}$. Fig. 4 is a schematic diagram showing the experimental layout.

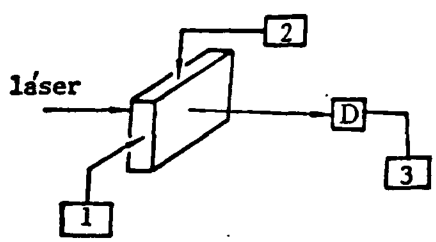

Fig. 4. Experimental layout:
1, 2. AO power supply
3. Laser power dynamometer

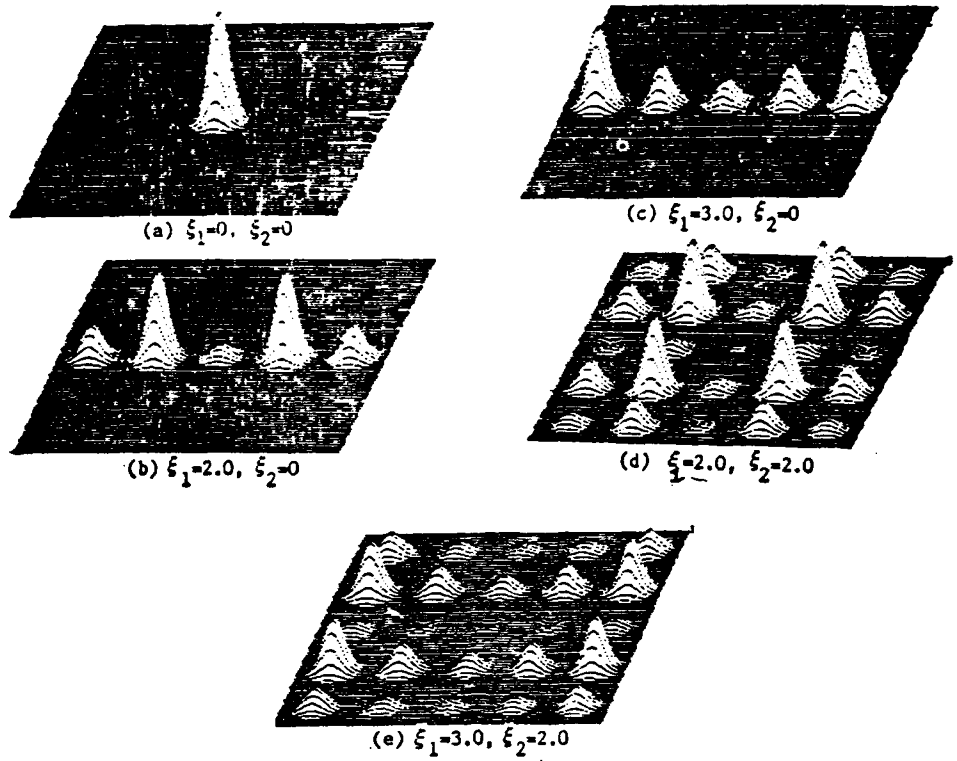

Fig. 3. Acousto-optical diffraction patterns

In the experiments, various levels of diffraction efficiency in several situations are measured; the results are listed in Table 1 [No Table 1 included within the given text pages--Tr.]. According to the experimental results, the diffraction graph of the spatial distribution corresponding to the experiment was plotted on a computer, as shown in Fig. 3. In the figure, the peak height is the relative light intensity.

From the calculation of Eq. (8), the experiments and theory are in fairly good agreement. As to the minor discrepancy between diffraction efficiency and its theoretical value, this is due to different diffraction efficiency η in this kind of apparatus. The diffraction efficiency of the apparatus of this

arrangement is

$$\eta_p = J_p^2\left[\xi_1 \frac{\sin\left(\frac{1}{2}\alpha_0\theta_1\right)}{\frac{1}{2}\alpha_0\theta_1}\right], \quad \eta_q = J_q^2\left[\xi_2 \frac{\sin\left(\frac{1}{2}\alpha_p\theta_2\right)}{\frac{1}{2}\alpha_p\theta_2}\right], \tag{10}$$

It is assumed here that incidence is first on the apparatus $\xi = \xi_1$. Since the diffracted light exiting from the first acousto-optical apparatus is not vertically incident at the second apparatus, the incident angle differs with different levels P. For vertical incidence onto the y-z plane, that is, $\alpha_0 = 0$, the diffraction efficiency is

$$\eta_{p,q} = J_p^2[\xi_1] J_q^2\left[\xi_2 \frac{\sin\left(\frac{1}{2}\alpha_p\theta_2\right)}{\frac{1}{2}\alpha_p\theta_2}\right], \tag{11}$$

Note that $[\sin(\alpha_p\theta_2/2)/(\alpha_p\theta_2/2)]<1$, therefore the variation of $\eta_{p,q}$ with P_{s2} becomes slower. The slowdown is different for different diffraction levels exiting from the first acousto-optical modulator.

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